SPECIFICATION

To whom it may concern:

Be it known that We, Gary L. Frederick, residing at 1733 Brandon Road, Rockford, IL 61107, and Richard A. Rose, residing at 6426 Greystone, Roscoe, IL 61073, both citizens of the United States, have invented a new and useful METHODS AND APPARATUS FOR SENSING ANGULAR POSITION AND SPEED OF A ROTATABLE SHAFT UTILIZING LINEARIZED ANNULAR MAGNET AND COMMUTATED RATIOMETRIC HALL SENSORS of which the following is a specification.

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METHODS AND APPARATUS FOR SENSING ANGULAR POSITION AND SPEED
OF A ROTATABLE SHAFT UTILIZING LINEARIZED ANNULAR MAGNET AND
COMMUTATED RATIOMETRIC HALL SENSORS

5   Cross-references to related applications: This
application claims the priority benefit of U.S. Provisional
Patent Application S/N 60,272,200, filed February 28, 2001.

       Reference to microfiche appendix for computer programs
10   - none.

            Background of the Invention
     1. Field of Invention
15   The present invention relates generally to rotary shaft
angular position and speed sensors.
        More specifically, the invention relates to contactless
angular sensors adapted to provide linear output signals
proportional to shaft speed and position for full 360 degree
20   rotations of the shaft, and which, while suitable for use
with other rotary shaft elements, is particularly useful in
connection with sensing the angular position and speed of a
torque transmitting shaft extending therethrough.

25   2. Description of Prior Art
        Shaft angular position sensing has historically been
accomplished using potentiometers, synchros, or resolvers
that rely on low reliability electrical contact arrangements
such as electrical brushes and wipers. Shaft rotational
30   speed sensing has historically been accomplished utilizing
magnetic tachometers which also rely on brush contacts.
Newer technologies for angular position and speed sensing

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include optical encoders which are unreliable in low temperature, moist environments. The need for high reliability shaft angle sensing for aircraft control surfaces and closed loop actuators has led to the application of rotary variable differential transformers (RVDTs). Unfortunately, these sensors are substantially more expensive and require sophisticated and expensive demodulation electronics to obtain useable output signals. Shaft speed sensing for high-reliability applications have often utilized magnetic pickoffs which sense the frequency of passing of a gear tooth or lobe. For reliable implementation, these sensors also require relatively expensive electronics packages.

As a result, recent efforts to achieve a lower-cost, yet reliable and accurate apparatus for sensing angular position and speed of a rotary shaft have included attempts to utilize less expensive sensor elements such as Hall effect devices or magnetoresistive (MR) sensors that are capable of generating an electrical output signal when exposed to a rotating magnetic field. Hall effect sensors utilize a current-carrying semi-conductor membrane to generate a low voltage perpendicular to the direction of current flow when subjected to a magnetic field normal to the surface of the membrane. Magnetoresistive sensors utilize an element whose resistance changes in the presence of a changing external magnetic field.

One group of prior art using these magnetic field sensors provide an output which is digital in nature, generating pulses as a functions of shaft speed or discrete signals for incremental shaft angles. Nichols, U.S. Patent 4,373,486, Schroeder, U.S. Patents 5,731,702 and 5,754,042, and Seefeldt, U.S. Patent 5,744,950, use permanent-magnet

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biased Hall effect devices and magnetoresistive sensors, respectively, to sense the passage of notches on a shaft-driven wheel for engine ignition control and shaft speed control. Kajimoto, U.S. Patent 5,574,364, utilizes magnets

5   imbedded into or polarized into the surface of a rotating wheel to provide a changing magnetic field direction as the surface of the wheel passes the sensors. The digital output signals require use of a microcomputer to practically implement their sensing and control functions. None of the

10   above arrangements provide for an analog output representative of shaft speed.

Some devices use magnetic field sensors to provide analog output signals as a magnet attached to a shaft is rotated. van den Berg, U.S. Patent 5,650,721, shows a two-

15   pole rectangular bar magnet rotating over a giant MR layer. The rotation of the transverse field between the poles creates a unique, sine-wave-shaped analog output over 180 degrees of rotation. However, linear output range is less than 60 degrees. Lochmann, U.S. Patent 6,064,197, adds a

20   Hall effect device to sense axial field direction and provide a unique, but nonlinear, signal over 360-degrees. Andräet, U.S. Patent 5,796,249, proposes the integration of at least three MR Wheatstone bridges under the transverse field of a bar magnet to provide a set of nonlinear outputs

25   that can be used to calculate a unique shaft angle. Häberli, International Publication WO98/54547, proposes a similar scheme utilizing two pairs of Hall effect sensors located on diagonals under a square magnet to generate approximate sine and cosine signals as the shaft and magnet

30   are rotated, and from which the shaft angle is calculated. Muth, U.S. Patent 5,602,471, proposes use of multiple MR bridges to generate a variety of phase-spaced sinusoidal

signals. The signals are forced to saturate within their linear range and then added to provide a summed output which is overall a linear function of shaft rotations, but which can exhibit a variety of gain variations and

5   discontinuities. None of these analog sensors lend themselves to being packaged around an axially continuing shaft, a feature desirable for compactly integrating angular sensor function into an electromechanical actuator or other torque carrying device.

10   Other analog shaft angle sensors using magnetic flux sensors have attempted to increase the linear operating range of typically sinusoidal signals by shaping the magnets or pole pieces. Wu, U.S. Patent 5,159,268, has generated a bell or oblong shaped two-pole magnet to get a linear range

15   approaching 180-degrees. Rountos, U.S. Patent 5,850,142, uses a pair of convex magnets and a spherical pole piece to generate a linear range of up to plus and minus 30 degrees for joysticks. Dawley, U.S. Patent 4,719,419, uses a monopolar annular magnet, either mounted eccentric to the

20   shaft or nonuniformly magnetized, to create a useable linear output of +/- 45 degrees. Nakamura, U.S. Patent 4,425,557, and Tomczak, U.S. Patent 4,570,118 incline the sensor magnets relative to the axis of rotation in an attempt to improve output linearity. Luetzow, U.S. Patents 5,444,369

25   and 6,137,288 and Herden, U.S. Patents 5,861,745 and 6,130,535 use a combination of shaped magnets, pole pieces, and axis offsets to get a linear output range approaching 180-degrees.

        Overall, the prior contactless shaft angular position

30   and speed sensing apparatus are either adapted to provide only a digital output signal that must be further processed or manipulated with additional components, require magnetic

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elements manufactured with non-standard shapes, do not provide a useful linear operating range, or do not lend themselves to being packaged such that the sensed shaft can extend fully through the sensor components.

5   Thus, it is apparent that there is a need for a high-reliability, low cost, rotary shaft sensor that is simple to manufacture, can provide linear output of both angular position and speed over a full 360 degrees of rotation, and can be packaged around a torque-carrying element such as

10   associated with a typical rotary actuator.

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Summary of the Invention

The primary aim of the present invention is to provide
an improved contactless rotary shaft angular position and
5   speed sensing system that allows a torque carrying shaft to
pass therethrough. This enables packaging of a high-
reliability contactless sensing system within, for example,
a rotary actuator.

Another objective of the invention is to provide such
10 improved contactless sensors that produce analog output
signals with enhanced linear operating ranges, but at
relatively low cost, as compared with prior sensors of the
same general type.

A detailed objective is to achieve the foregoing by
15 providing an annular magnet that has been uniquely
magnetized to achieve an enhanced linearly varying flux
density operating range as the magnet rotates, and magnetic
field sensor elements that provide a linear output signal
proportional to the strength of the linearly varying flux
20 density sensed.

Another detailed objective is to provide such annular
magnet and magnet field sensors operable to sense the
angular position over a linear operating range of at least
120 degrees of rotation.

25   Another objective of the invention is to provide a
sensor that produces an output voltage signal proportional
to shaft angular position and/or speed through a full 360
degrees of rotation.

The invention also resides in unique implementation of
30 commutation logic to effect provision of the proportional
output voltage through 360 degrees of shaft rotation.

These and other objects and advantages of the present invention will become apparent from the following written description and accompanying drawings.

Briefly, the objectives of the invention are
5   accomplished in a basic preferred embodiment by fixing a unique annular magnet around the rotary shaft. The magnet, preferably ALNICO 8 or samarium cobalt for thermal stability, is magnetized to have two poles 180-degrees apart on its radial surface. A slug of magnetic iron is placed in
10   the core of the magnet during the magnetization process to effect a pole strength that increases linearly from a neutral position between the poles to within 30 degrees of each pole. This magnet can be manufactured very accurately and efficiently for use in a shaft position sensing system
15   that can produce linear analog output signals over a +/- 60 degree range of rotation. The magnetic field sensor elements utilized in preferred embodiments are a pair of ratiometric Hall effect devices placed 180 degrees apart around the circumference of the magnet. The sensor elements
20   are spaced from the magnet wall to avoid saturation when the poles rotate into angular alignment therewith. The output signals of the sensor pair are filtered and connected to opposite inputs of an operational amplifier. The filter network can be configured with resistors to provide a
25   linearly amplified voltage that is proportional to the shaft angle. Replacement of the input resistors with capacitors allows the low-noise signal from the Hall effect devices to be differentiated for an output voltage that is proportional to shaft rate of rotation. A resistor and capacitor
30   combination can be used to provide an output which is a combination of shaft position and speed, a desirable feature for sensing output shaft position for closed-loop actuator

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control. Magnetoresistive sensors can also be utilized to implement the magnetic field sensing function.

A second embodiment utilizes three pairs of Hall effect devices which are uniformly spaced 120-degrees around the circumference of the annular magnet. This provides three linear sensor output segments, each with a useful linear range of 120 degrees of shaft rotation, and which can be combined for a linear signal relationship to 360 degrees of shaft rotation.

The Hall effect sensor signals from each pair are also utilized to provide a signal for commutation of the linear segments to a common output port. The signals from each Hall effect device pair are fed to opposite inputs of a high gain comparator. The output state of the comparator switches as the polarity of the magnetic field from the annular magnet changes as it passes by the sensors. One of the three comparator output signals switches every 60 degrees. These three commutation signals are fed to a NOR logic circuit which provides the signals to switch an analog multiplexer. The amplified analog outputs from each sensor pair are provided as inputs to the switch. As the shaft rotates, the output of the logic circuit closes the appropriate solid-state switch for the input segment that is in its 120-degree linear range. Implementation of this circuit as a solid-state tachometer is provided by configuring the input amplifier as a differentiator. Each of the analog signals to the switched gate will be proportional to shaft rotational rate when the switches are closed to provide an analog output voltage proportional to rate and direction of rotation.

A third embodiment, using the same switching logic and sensor configuration, provides a linear, analog output

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voltage proportional to position for 360-degrees of shaft
rotation. For preferred performance, the gains of each
analog channel are matched in the linear region. The output
of the first segment is referenced to a fixed voltage. The
5   output of the second segment is referenced to the same fixed
voltage plus the gain in volts/degree times 120-degrees.
The third segment is referenced to the same fixed voltage
plus the gain times 240-degrees. As the shaft rotates, the
linear, variable-referenced segments are individually
10   switched to provide an output voltage proportional to shaft
angle over a full 360-degrees of operation.

A fourth embodiment disclosed utilizes a microcomputer
to implement the logic and switching functions described
above. The individual amplified sensor pair outputs are
15   converted to digital format prior to processing. An
additional refinement offered by this approach is comparison
of the sensor segment outputs at the switch points, and
subtraction of the difference to eliminate discontinuities
in the final output characteristic.
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Brief Description of the Drawings

Figure 1 is a fragmentary cross-sectional view of angular position and speed sensing apparatus in accordance with the invention, including an annular magnet fixed around a rotary shaft, and a pair of magnetic field sensor elements fixed to a non-rotating housing.

Figure 2 is a fragmentary cross-sectional taken substantially along the line 2-2 of Figure 1, and showing a top plan view of the annular magnet and magnetic field sensor elements.

Figure 3 is a top plan view of a conventional magnetizing coil, and showing the annular magnet of Figure 1 and a cylindrical magnetic iron core positioned therein as during magnetization of the annular magnet.

Figure 4 is a cross-sectional side view of the magnetizing coil of Figure 3, and showing the annular magnet and iron core positioned therein.

Figure 5a is a graph depicting a differential output voltage from the magnetic field sensors for rotation of an annular magnet that has not been magnetized with an iron core in its center, and of a differential output voltage resulting from a solid cylindrical magnet shown in dashed lines.

Figure 5b is a graph depicting a differential output from the magnetic field sensors for rotation of an annular magnet that has been magnetized with an iron core in its center.

Figure 6 is a schematic representation of a preferred embodiment for sensing the magnetic field around the annular magnet, and amplifying, and filtering the sensor element output signals.

Figure 6a is a schematic representation similar to
Figure 6 of a modified circuit adapted to provide an output
signal proportional to angular position.

Figure 6b is a schematic representation similar to
5   Figure 6 of a modified circuit adapted to provide an output
signal proportional to rate of rotation.

Figure 7 is a graphical representation of voltage
output versus +/- 60 degrees of magnet rotation for the
circuit shown in Figure 6a configured as an angular position
10   amplifier.

Figure 8 is a top plan view similar to Figure 2 of an
alternate embodiment sensor provided with an annular magnet
and three pairs of magnetic field sensors positioned at 120-
degree radial intervals around the angular magnet.

15   Figure 9a is a graphical representation of the
amplified voltage from the three pairs of magnetic field
sensors shown in Figure 8 as the annular magnet rotates.

Figure 9b is a graphical representation of comparator
output states for each of the three pairs of magnetic field
20   sensors shown in Figure 8 as the annular magnet rotates.

Figure 10 is a schematic representation of a
commutation circuit adapted to switch the amplified voltages
such as shown in Figure 9a from the three pairs of magnetic
field sensors to a common output when each is in its
25   positive-slope linear operating range.

Figure 11 is a graphical representation of the output
from an analog tachometer implemented from the configuration
and circuits shown in Figures 6, 8 and 10.

Figure 12 is a graphical representation of the output
30   from a 360-degree shaft angle position sensor implemented
from the configuration and circuits shown in Figures 6, 8
and 10.

Figure 13 is a schematic representation of an alternate
embodiment for a 360-degree shaft rotation sensor that
utilizes a microcomputer to perform the logic, summing, and
dynamic signal processing as well as to remove output
5   discontinuities at the 120-degree switch points.

For reference purposes, the following reference
numerals correspond to the following items indicated in the
drawings and discussed in detail below:

10   —   sensor

12   —   annular magnet

12a   —   annular magnet blank

14   —   shaft

16   —   magnetic field sensor elements (H_i)

18   —   bearings

20   —   housing

22   —   printed circuit board

24   —   cylindrical iron plug

26   —   magnetizing coil

26a   —   magnetizing flux lines

28   —   sensor output signal for conventional annular magnet

30   —   sensor output signal for cylindrical magnet

32   —   sensor output signal for annular magnet

34   —   signal processing circuit

36   —   input RC filtering network

38   —   input network resistor (R_I)

40   —   input network capacitor (C_I)

42   —   operational amplifier

44   —   feedback network

46   —   feedback resistor (R_o)

48   —   feedback capacitor (C_o)

50   —   alternate sensor

52   —   comparator

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54	–	NOR gate
56	–	analog multiplexing switch
58	–	commutation logic implementation circuit
60	–	microprocessor
62	–	analog to digital converters
64	–	digital to analog converters

A_i	–	multiplexer address line
G_θ	–	angular position gain (voltage per degrees rotation
H_i	–	magnet field sensor/output signal
i	–	(in subscript) individual-unit designator
i'	–	(in subscript) individual-unit designator
RPM	–	revolutions per minute
$S_{ii'}$	–	comparator output signal
$V_{ii'}$	–	output voltage from signal processing circuit
$V_{REFii'}$	–	bias/reference voltage
V_H	–	supply voltage to magnetic field sensors
$V_{POSITION}$	–	angular position output signal from microprocessor
V_S	–	supply voltage to magnetic field sensor elements
V_{SP1}	–	switch point voltage
V_{RATE}	–	rate of rotation output signal from microprocessor

θ	–	shaft angle position

Detailed Description of the Invention

For the purpose of promoting an understanding of the principles of the invention, reference will now be made to
5   the embodiments illustrated in the drawings and specific language will be used to describe such embodiments. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended, such alterations and further modifications in the illustrated device, and such
10   further applications of the principles of the invention as illustrated therein being contemplated as would normally occur to one skilled in the art to which the invention relates.

Alternate embodiment angular position and speed shaft
15   sensors shown in the drawings and described herein comprise one pair of magnetic field sensor elements, and three pairs of magnetic field sensor elements. From these embodiments, additional alternate embodiments are developed, including apparatus for sensing and providing an output signal that is
20   proportional to shaft angular position and speed through 120 degrees of rotation, shaft angular position and speed through 360 degrees of rotation, and shaft speed through multiple revolutions. Those skilled in the art will recognize that additional alternate embodiments may be
25   constructed within the scope of the invention.

Referring now to Figures 1 and 2, there is shown one embodiment of a shaft sensor 10 in accordance with the invention. Briefly, the sensor 10 includes a magnet 12 connected for rotation with shaft 14 for which the angular
30   position (θ) and/or speed ($d\theta/dt$) is to be sensed, magnetic field sensor elements 16 adapted to sense the strength of magnetic flux of the magnet as it rotates with the shaft and

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to provide an output signal indicative of the magnetic field sensed, and signal processing circuitry adapted to process the output signal from the sensor elements and to provide an indication of the angular position and/or rate of rotation

5   of the shaft therefrom.

The magnet 12 is annular in shape, and is magnetized to have two radial poles, designated "N" and "S" in Figure 2, of opposite polarity located 180 degrees from each other. The magnet is located around the shaft 14, and is fixed to

10   the shaft such that it rotates on a one-to-one basis coaxial therewith. For low temperature sensitivity, the annular magnet is preferably made from an ALNICO 8 or samarium cobalt magnet material.

As the magnet 12 rotates, the change in magnetic flux

15   is sensed differentially by a pair of stationary magnetic field sensors 16 (designated individually as H_1 and H_2) that each generate a periodic output voltage signal proportional to the magnetic flux density at the sensor. In preferred embodiments, these sensor elements are Hall effect devices,

20   but magnetoresistive (MR) sensors can be made to function similarly by one skilled in the art.

Figures 1 and 2 illustrate how the use of an annular magnet 12 and radial magnetic field sensors 16 allow a shaft 14 of significant size to pass through the sensor

25   components, allowing for a compact package and robust design. This is especially advantageous when sensing the output shaft position and speed for a torque producing assembly such as an electromechanical actuator. In such instances, the shaft can be mounted on large bearings 18

30   located directly in the actuator housing 20, and the magnetic flux sensors can be rigidly attached to a printed circuit board 22 which is in turn attached to the rigid

mechanical housing. Thus, the sensor components can be
mounted within the actuator housing for a compact overall
actuator. Alternately, the sensor components may be located
in a separate sensor housing, and provided with an interface

5   stub shaft or other coupling arrangement for connecting the
rotatable annular magnet to the end of the rotary element
for which the angular position and/or speed is to be sensed.

        In accordance with one aspect of the invention, the
annular magnet 12 is uniquely adapted to provide for an

10   enhanced linear operating range in the sensing of angular
position of the shaft 14. More specifically, the magnetic
field lines generated by the annular magnet are shaped
during the magnetization process such that the strength of
the magnetic field increases and decreases substantially

15   linearly, and thus the output signals from the sensor
elements 16 remain substantially linear, through an
operating range of at least +/- 60 degrees and up to
approximately +/- 70 degrees of rotation from the neutral
position as shown in Figure 2.

20   In carrying out this aspect of the invention, a solid
magnetic iron plug is temporarily inserted through the
center of an annular magnet blank during its magnetization
to produce a magnetic flux density characteristic in the
resulting magnet that varies substantially linearly through

25   at least +/- 60 degrees of rotation from the neutral
position. Figures 3 and 4 illustrate the magnetization of
annular magnet 12 in accordance herewith in a conventional
magnetizing coil 26 adapted to develop magnetizing flux
lines generally indicated by dashed lines 26a during the

30   magnetization process. The annular magnet blank 12a and the
iron core 24 are positioned in the magnetizing coil 26
cross-wise of the magnetizing flux lines 26a to produce the

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two radial poles designated N and S and the desired magnetic flux characteristic.

For further understanding, reference is made to Figures 5a and 5b in which the change in magnetic flux density normal to a radially spaced Hall effect device (i.e., the flux density acting radially with respect to the center of the magnet) is illustrated in the form of differential sensor output voltages as three different magnets are rotated through 360-degrees.

Figure 5a illustrates a magnetic field sensor output signal 28 associated with an annular, two-pole ALNICO 8 magnet having an outer diameter of 1.125 inches and an inner diameter of 0.750 inches, and having been conventionally magnetized in a uniform magnetizing field 26a such as in magnetizing coil 26 with only air in its inside diameter. Inspection of Figure 5a reveals that the conventionally magnetized annular magnet develops an output wave form of a concave or tangent-like curve 28 as the magnet is rotated between approximately +/- 60 degrees to +/- 70 degrees from the neutral position between the poles.

A similarly sized and magnetized two-pole cylindrical, solid-center magnet results in a convex or generally sine-shaped curve designated as 30 shown in dashed lines in Figure 5a as the magnet is rotated.

By temporarily installing a solid magnetic iron plug in the center of an annular magnet blank during magnetization, the flux line pattern of the resulting annular magnet begins to approach that of a solid cylindrical magnet. With the proper outside diameter, and ratio of outside diameter to inside diameter, and magnetizing the annular blank with an iron plug slidably but snugly inserted into its center, the concave (tangent-shape) and convex (sine-shape)

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characteristics cancel each other to produce a highly linearly changing flux density, and thus a highly linear magnetic field sensor voltage output for over +/- 60 degrees from the neutral position as shown by wave form 32 in Figure

5   5b, with acceptable linearity up to approximately +/- 70 degrees for many applications. In particular, with these procedures, linearity of less than +/- 1 percent can be easily achieved for +/- 60 degrees of rotation, and a linearity of less than +/- 3% can be achieved over an

10   operating range of approximately +/- 65 degrees.

The above-sized annular magnet, having an OD of 1.125 inches and an ID of 0.75 inches, is of a suitable diameter size and ratio to exhibit the desired linear characteristics (e.g., +/- 1% linearity) when magnetized with the

15   cylindrical iron plug for up to at least +/- 60 degrees rotation. Other sized annular magnet configurations, with appropriate size and diameter ratios to produce the same linear flux density characteristics will be developed by those skilled in the art either through testing or through

20   analytical analysis.

Thus, the sensor 10 exhibits improved contactless position sensing with a linear range of over 120 degrees rotation, allows the shaft 14 to extend through the sensor components, and is efficient to manufacture due to its

25   compact design, simple magnet 12 shape and magnetizing method. This embodiment forms the basis for the following embodiments which, in conjunction with a signal processing circuit such as shown in Figure 6 and implemented in circuit board 22, provides for sensing of shaft position or speed

30   over 120 degrees of rotation; and with further refinements described subsequently, enables continuously sensing shaft position and speed for a full 360-degrees of rotation.

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Figure 6 presents a conventional and well-known circuit
34 for differentially amplifying the output voltage signals
H_1 and H_2 from the Hall effect devices 16, and performing
dynamic compensation or filtering, which allows the circuit
5   output voltage V_{12} to indicate shaft 14 position, speed, or a
combination of both. For example, as the shaft rotates
clockwise from the neutral position shown, the output
voltage from H_1 increases and the output voltage from H_2
decreases. The voltages from the Hall effect devices are
10   fed to input RC filtering networks 36 each including a
resistor 38 (R_I) and a capacitor 40 (C_I) in parallel. The
input network voltages create currents into operational
amplifier 42. A feedback network 44 includes a resistor 46
(R_O) and capacitor 48 (C_O) in parallel. Voltage V_{REF12} is
15   supplied to the operational amplifier to establish a circuit
output voltage signal V_{12} at a desired level. V_H is the
supply voltage to the Hall effect sensors, and V_S is the
supply voltage to the operational amplifier. From this
basic amplifier circuit, specific circuits are utilized as
20   discussed below for desired output signals in accordance
with the invention.

When an output voltage proportional to shaft position
is desired, the input network capacitors 40 are omitted as
shown in Figure 6a. The result is that the differential
25   output voltages H_1 and H_2 from the Hall effect devices 16
are amplified linearly by the ratio of the output resistor
46 to the input resistor 38. The output capacitor 48 works
with the output resistor 46 to suppress high frequency
noise. A typical amplified output voltage V_{12} versus shaft
30   position is depicted in Figure 7. This figure demonstrates
the nature of the quiet output signal V_{12} which is linearly

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proportional to shaft angle for over 120-degrees of rotation.

Since the current invention results in a shaft, a magnet, and magnetic flux sensors which can be rigidly constrained to be immune from vibration, and since there are no brushes or contacts, the voltage signals can be made to be extremely noise-free. This makes it possible to differentiate, or measure the slope of the shaft position signals to provide an economical, contactless equivalent to a tachometer.

In this mode, the input resistors 38 are omitted, resulting in circuit 34b shown Figure 6b, and the output of the circuit is given by the equations,

$$V_{12} = R_O \, C_I \, \frac{d(H_1 - H_2)}{dt}$$

and

$$\frac{d(H_1 - H_2)}{dt} = \frac{d(H_1 - H_2)}{d\theta} \frac{d\theta}{dt} = \frac{d(H_1 - H_2)}{d\theta} \times 360 \, \frac{deg}{rev} \times \frac{1 \, min}{60 \, sec} \times RPM_{shaft}$$

Substituting the second equation into the first yields:

$$V_{12} = 6 R_O \, C_I \frac{d(H_1 - H_2)}{d\theta} \times RPM_{shaft}$$

Thus, the output voltage V_{12} is proportional to shaft speed over the 120 degree linear sensor range.

For use as a feedback sensor such as in a closed-loop actuation system, input resistor 38 and input capacitor 40 will typically be selected to provide an output voltage signal V_{12} that is proportional to both shaft speed and position to provide a well-damped actuator positioning system. As can be seen from Figure 1, this can all be achieved in a compact design with the sensor components packaged in the actuator housing around the actuator output shaft 14. Those skilled in the art will appreciate that

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alternate amplifying circuits may be provided, for amplifying and conditioning the magnetic field sensor output voltage signals, to achieve a desired circuit output voltage signal V_{12} that is proportional to the position and/or speed

5   of the shaft.

Those skilled in the art will also understand that, although an angular position sensor hereof may be alternately provided with a single magnetic field sensor and an amplifier circuit for one input, the use of two magnetic

10   field sensors whose outputs change in opposite directions as the shaft rotates, and associated differentially amplifying circuits, provides for a sensor with decreased sensitivity to temperature variations, variations in the magnet and between magnets, and variations in the characteristics of

15   the magnetic field sensors themselves due to, for example, manufacturing tolerances. And the use of two flux sensors spaced 180 degrees apart, with the annular magnet having its poles at 180 degrees, provides for a simplified amplifier circuit as compared with a circuit adapted for use with

20   sensors intentionally spaced at a different angle.

Figure 8 presents the basis for preferred embodiment sensors 50 which utilize three pairs of equally spaced magnetic field sensors 16, designated individually as H_1 and H_2, H_4 and H_3, and H_5 and H_6, and which permit sensing of

25   shaft 14 rotation for a full 360-degrees. The annular magnet 12 and annular Hall effect sensor circuit board 22 make it easy to package the two additional sensor pairs radially spaced outwardly from and generally aligned around the annular magnet as shown in Figures 8 and 1. The magnetic

30   field sensor pairs 16 are preferably spaced 120 degrees apart. During operation, each pair will have a unique 120 degree linear output voltage range that is phased 120

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degrees from the output of the other two pairs. The
resulting output voltage signals V_{12}, V_{43} and V_{56} from three
identical amplifier circuits such as represented in Figure 6
and set up in the angular position (i.e., proportional)
5   mode, is shown graphically in Figure 9a. Figure 9b shows a
corresponding phasing chart for the differential Hall effect
device signals being output from a comparator. The
comparator output signals are designated S_{12}, S_{56}, and S_{43},
with the subscripts corresponding to the Hall effect devices
10   from which the output signals are calculated.

       To implement a sensor with a 360 degree output
capability, the current invention utilizes linear, same-
sloping signals from each Hall effect device sensor pair.
Examining the timing charts in Figures 9a and 9b, it will be
15   understood that the following set of logic equations yield
the desired result:

       (1) If S_{12} is high and S_{43} low, use V_{56}.
       (2) If S_{56} is high and S_{12} low, use V_{43}.
       (3) If S_{43} is high and S_{56} low, use V_{12}.

20   These logic equations may be implemented utilizing the
comparators 52, "NOR" gates 54, and analog multiplexing
switch 56 as shown in Figure 10. High (or positive)
indicates that the differential voltage from the Hall effect
device pair is greater than the mean of the wave form; low
25   (or negative) indicates that the voltage is less than the
mean voltage of the wave form.

       Referring to Figure 10, the resulting logic for the
multiplexer 56 address lines A_1 and A_0 is summarized in the
following table:

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HALL EFFECT DEVICE OUTPUT VOLTAGES (INPUTS TO COMPARATORS)			COMPARATOR OUTPUT VOLTAGES			MULTIPLEXER ADDRESS LINES		SWITCHED OUTPUT
H_1-H_2	H_5-H_6	H_4-H_3	S_{12}	S_{56}	S_{43}	A_1	A_0	V_{OUT}
X	-	+	X	0	1	0	0	V_{12}
+	X	-	1	X	0	0	1	V_{56}
-	+	X	0	1	X	1	0	V_{43}

Where: +   means the input signal is positive

            -    means the input signal is negative

            X   means the input signal does not impact the logic output,

            0   means a logic low (0 volts typical)

            1   means a logic high (5 volts typical)

This states that:

(1) A_0 is logical 0 when (H_4 – H_3) is positive or (H_1 – H_2) is negative, and

(2) A_1 is logical 0 when (H_1 – H_2) is positive or (H_5 – H_6) is negative.

These logic relationships may be written using logic notation as follows:

(1) $A_0 = (H_1 - H_2) \cdot \overline{(H_4 - H_3)}$ or

$A_0 = \overline{\overline{(H_1 - H_2)} + (H_4 - H_3)}$ or

$\overline{A_0} = \overline{(H_1 - H_2)} + (H_4 - H_3)$, and

(2) $A_1 = (H_5 - H_6) \cdot \overline{(H_1 - H_2)}$ or

$A_1 = \overline{\overline{(H_5 - H_6)} + (H_1 - H_2)}$ or

$\overline{A_1} = \overline{(H_5 - H_6)} + (H_1 - H_2)$.

One embodiment for implementing these commutation logic equations is shown in Figure 10. In this instance, the commutation logic equations are implemented using four NOR gates 54a-d where NOR gates 54b and 54c are configured as

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inverters. Thus, using the same Hall effect devices 16 that
detect the analog position of the shaft 14, three
comparators 52, four NOR gates 54, and a multiplexer 56, the
required commutation logic can be simply implemented.

5 Typically, this will require only three additional
integrated circuits since the comparators and NOR gates are
readily available in compact Quad packages.

The output voltage signal V_{out} of the commutation
circuit 58 of Figure 10 is equally comprised of the three

10 switched input signals V_{12}, V_{56}, and V_{43}. The slope
characteristic (i.e., gain G_θ) of each of these input
signals is matched relatively closely to the characteristic
of the other two in the 120-degree linear operating ranges.
Referring to Figure 6, the gains can be matched by

15 refinement or adjustment of the resistance of associated
feedback resistors 46.

When configured as a tachometer for sensing complete
revolutions of the shaft 14, the sensor 50 includes three
Hall-device sensor pairs 16 arranged as shown in Figure 8,

20 three amplifier circuits 34b generally depicted in Figure
6b, and the commutation circuit 58 shown in Figure 10. The
input resistors 38 are omitted from the amplifier circuits
to create an identical differentiating circuit for each
segment, producing outputs voltages V_{12}, V_{56}, and V_{43} that are

25 proportional to shaft speed. The mean operating level of
each output segment V_{12}, V_{56}, and V_{43} is adjusted to equal
voltages levels by tuning of the associated bias reference
voltage V_{REF}. Figure 11 shows a graph of a typical output
voltage V_{out} from the sensor 50 versus rotational rate for a

30 continuously rotating shaft. This produces a contactless
equivalent to a brush tachometer without the low reliability
and shorter life associated with brush tachometers, is

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easily integrated into an overall actuator or motion control package, and requires only a few inexpensive components to implement.

5   When configured as a 360 degree shaft position sensor, the sensor 50 includes the same overall circuit blocks, except that the amplifier circuits are provided as per Figure 6a, without input capacitors 40, and the input resistors 38 are selected in conjunction with output resistors 46 to provide the same slope (i.e., gain G_θ) for

10 each linear operating segment. The bias reference voltages V_{REF} are individually adjusted so that, at the switch points between the linear operating regions of each Hall sensor pair 16, the starting voltage of a subsequent line segment is equal to the ending voltage of the preceding line

15 segment. Assuming, for example, V_{12} is biased to provide the initial output from 0 to 120 degrees of shaft rotation, a typical set of bias voltages would be as summarized below:

V_{REF12} = G_θ x 60 degrees,

V_{REF56} = V_{REF12} + G_θ x 120 degrees, and

20   V_{REF43} = V_{REF12} + G_θ x 240 degrees.

By way of example, Figure 12 shows a graph of a typical output voltage V_{out} versus rotational angle, including same-slope voltage segments, and equal switch point voltages V_{SP1} and V_{SP2} between the regions of linear operation of the pairs

25 of flux sensors 16, for a sensor 50 configured with a gain of 0.018 volts/degree and V_{REF12} of 1.6 volts. As a result, this arrangement produces a contactless equivalent to a brush potentiometer without the low reliability and shorter life associated with brush potentiometers, is easily

30 integrated into an overall actuator or motion control package, and requires only a few simple components to implement.

25

Referring to Figure 13, the logic and switching functions of the commutation circuit 58 as shown in Figure 10 can be alternately performed by a microcomputer 60. The position differentiation function can also be performed

5   mathematically to allow the analog amplifier circuit of Figure 6 to be configured for position sensing only, with the microcomputer calculating 360 degree angular position and angular rate (i.e., speed) from the time rate of change in position. In the embodiment shown, the Hall effect

10   device sensor 16 outputs (H_i) are input to the comparators 52 to provide the logic high and low signals indicative of the desired commutation switch points. The output signals (S_{12}, S_{56}, S_{43}) from these switches are input directly to the microprocessor. The Hall effect device sensor pair outputs

15   are also input to three amplifiers 42 with associated amplifier circuitry as in Figure 6, but with input capacitors 40 preferably omitted to configure the circuits for position sensing mode. The outputs V_{12}, V_{56}, and V_{43} of the amplifier circuits are then converted to digital format

20   signals by analog to digital converters 62 and the digital position signals are fed to the microcontroller. The software in the microcontroller performs at least the following functions to provide linear position and speed output characteristics ($V_{POSITION}$, V_{RATE}) over 360 degrees of

25   shaft 14 rotation:

(1) Commutation logic manipulation equivalent to that previously described and as illustrated in Figure 10 to process the proper analog voltage segments as a function of shaft angular position.

30   (2) Storage of voltage change between switch points to provide gain correction factors for each sensor output and

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for varying ambient temperatures and manufacturing
tolerances.

     (3) Application of digital biases (reference voltages)
to mathematically match the line segment values at the 120

5   and 240 degree switch points.

     (4) Computation of the rate of change of position to
provide an output proportional to shaft angular rate of
rotation.

     The digitally corrected and computed shaft position and

10   rate values are then output in digital format, or converted
to analog voltages $V_{POSITION}$ and V_{RATE} by digital to analog
converters 64. This embodiment produces highly accurate,
contactless shaft position and rate signals in both analog
and digital form, is easily integrated into an overall

15   motion control system, and involves only a few simple and
relatively inexpensive components to implement.

     From the foregoing, it will be apparent that the
present invention brings to the art new contactless angular
position and rotational speed sensor apparatus uniquely

20   adapted for use with a rotary shaft extending therethrough,
and for expanded linear sensing ranges as compared with
prior sensors of the same general type. By virtue of
providing an annular magnet through which the shaft extends
and that has been magnetized with a core temporarily

25   inserted through its center, a magnetic field sensor
stationed in a non-saturating position in the magnetic
field, and associated signal processing circuit, the sensor
unit is uniquely operable to provide an output signal that
is proportional to the angular position and/or speed of

30   rotation of the magnet and shaft through linear range
increment of at least 120 degrees of rotation. By virtue of
providing three magnetic field sensor pairs, each adapted

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for a linear operating range of 120 degrees and an output
signal that is 120 degrees out of phase from the signals of
the other pairs, signal processing circuitry including
application of gain and phase biased reference voltages to
5   the output signals from the sensor pairs, and switching
logic including use of the output signals from the sensor
pairs as switching signals to gate the signals to an output
summing amplifier when each pair is in its 120-degree linear
operating range, the rotational sensor is uniquely operable
10   to provide an output signal that is proportional to the
angular position and rotational speed of the shaft through a
full 360 degrees of rotation, and speed of rotation through
multiple revolutions.